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An Observational and Theoretical Study of Atmospheric Flow Over a Heated Island: Part I[1]

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ABSTRACT—In Part I of the two-part paper, we describe the results of a field program that was especially designed for testing the results of a theoretical model. The observations included measurements by an instrumented aircraft and a special surface network over an island with physical features that satisfy approximately the model assumptions. Panoramic cloud photographs and time-lapse movies of the clouds were also taken.

The observations show that evaporational cooling of the environment has an important influence on the behavior of perturbations induced by the heated island.

1. INTRODUCTION

When air flows over a localized heat source on the earth's surface, its properties are altered by the addition of heat from the underlying surface. Heat is transferred from the surface to the lowest atmospheric layers by small-scale diffusion. The heat in these layers is, in turn, transported to upper levels by penetrative convection and also by the ensuing larger scale circulations. Under favorable conditions, most notably in a tropical marine environment, precipitation may occur, accompanied by the release of latent heat of condensation; this additional heating may lead to the development of vigorous local perturbations. Heated islands under the influence of short-wave solar radiation provide an obvious example of a localized heat source. Here, in the absence of larger scale disturbances, the combined action of surface heating and friction can generate significant local mesoscale disturbances.

Observational Studies

Numerous islands in tropical oceans offer relatively controlled conditions for observing the effect of heated islands on the ambient atmosphere. Observations have demonstrated these islands to be preferred regions for significant convective scale disturbances when conditions are favorable. Malkus and McCasland (1949) have reported observing periodically spaced rows of cumulus clouds extending downwind from a small, essentially flat, island where orographic effects were negligible in cloud production. Again, observations over the small flat island of Anegada in the Caribbean area have shown that when there are no synoptic scale disturbances, the island produces showering clouds and that no precipitation was possible from any clouds except those produced by the island (Malkus 1963). Garstang (1967) has used observations over an extended period of time over the island of Barbados, West Indies, to stress the importance of eddy flux of momentum upon the flow over a heated island. The lake-effect phenomena are also analogous to the heated island phenomenon but on a relatively larger spatial scale. For example, frequent and often severe local mesoscale weather disturbances occur as cold continental-polar air moves across the unfrozen Great Lakes during late fall and early winter. In either case, these disturbances arise as a result of the combined action of surface forcing influences such as heating, friction, and topography. The occurrence and behavior of any such disturbance is intimately related to the structure of the prevailing flow and the intensity of temperature excess of the island over its surroundings. Other factors such as the size, shape, topography, and orientation of the island with respect to the prevailing flow also significantly influence these disturbances. However, some observational programs on heated islands have indicated that, for certain islands, the picture is not quite so simple and universal, especially in the presence of vertical shear in the prevailing flow (Garstang 1972).

Theoretical Studies

In the most basic terms, the heated island effect is the generalization of other phenomena, such as the sea-breeze circulation, which are commonly associated with differential heating. Numerical models, based upon the conservation laws of hydrothermodynamics, have been constructed to help understand the behavior of the flow over heated islands. Malkus and Stern (1953) and Stern and Malkus (1953) were the first to attempt a theoretical study of the heated island phenomenon by using linearized steady-state models. Smith (1955, 1957) developed a prognostic linearized model to study the flow over a heated island. More recently, Estoque and Bhumralkar (1969) have developed a general, theoretical, two-dimensional dry model to analyze properties of perturbations induced by the heated island. There are other numerical mesoscale models (e.g., Takeda 1971) that have integrated hydro-

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dynamic and thermodynamic equations using the initial wind with vertical shear. The results from these integrations are reasonably realistic.

Except for Takeda (1971), however, the previously mentioned heated island studies have not considered the microphysical processes of condensation, accretion, and evaporation. The growth and evaporation of precipitation accompanied by changes of phase provide sources and sinks of heat that influence the air motion. Release of latent heat during condensation provides an additional buoyancy, which may sustain an updraft and promote its subsequent growth. Also, mixing with cloud environment and evaporation of precipitation can lead to cooling and the formation of a downdraft.

Objective

The specific objective of this research is twofold. First, we want to formulate a general theoretical nonlinear model that can simulate the reaction of the atmosphere to surface heating and friction. The model is made more realistic by incorporating the processes leading to the initiation, growth, and depletion of precipitation together with the nonadiabatic feedback effects. We have also used the model to examine and analyze the dependence of the induced perturbations on the structure of the prevailing flow, the intensity of the heat source, and its orientation with respect to the prevailing flow. Secondly, we also want to verify our theoretical model results by specifically designed observational studies on the space and time scale of the perturbations induced by a heated island.

In Part I of this paper, we describe the results of our observational program, which was designed with the specific purpose of verifying the theoretical computations. In Part II, we will describe, in detail, the theoretical model and its results. We will also present a comparison between the theoretical and the observational results.

2. THE FIELD PROGRAM

Our theoretical model predicts the perturbations induced by a heated island of theoretically infinite length. Distributions of various meteorological variables are predicted on a vertical cross section for the duration of the daylight hours only. Since the ultimate test of the usefulness of a model is the degree to which it can simulate certain real atmospheric conditions, a field program was designed with a view to compare observations with the results of the theoretical model. We selected Grand Bahama Island, in the Caribbean Sea (26°N, 78°W), as the site of the field program mainly because it has essentially two-dimensional features and, therefore, has close correspondence with a two-dimensional theoretical heated island. The observational program was conducted during the period Aug. 20 through Aug. 29, 1970.

The Study Area

Observations were made *at* the site on Grand Bahama Island (GBI). The relative location of GBI is shown at

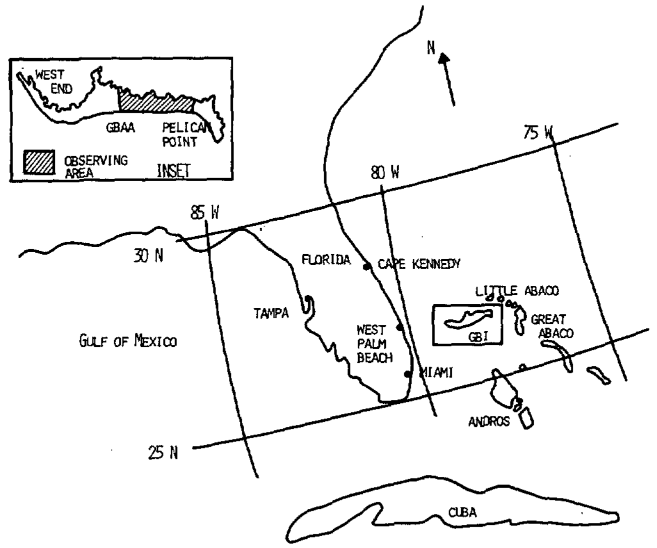

FIGURE 1.—Grand Bahama Island and vicinity. Inset shows the island with the selected observing area.

figure 1. The inset shows the selected observing area on the island. GBI is a long, narrow island; it is 130 km long with an average width of only 10 km. It has a nearly flat terrain, vegetated predominantly by thin pine trees of moderate (10–12 m) height. Also, there are good roads over the length and breadth of the island, which facilitated the installation of measuring instruments at any location of our choice. Despite the relatively small size of the island, it is large enough to produce significant effects on the atmosphere.

Climatological records describe the Bahama Islands as subtropical. The control of the climate during summer is the trade-wind system; from May to September the trades blow mostly from south through east. The trades persist throughout the year except for some seasonal variations such as an occasional hurricane or the intrusion of cyclonic and anticyclonic influences from the North American continent. The pressure over the general study area is highest in winter, but there is a secondary rise in summer with its maximum in July. The diurnal variation seldom shows any noticeable annual change. The temperatures show an annual range of 3°–6°C between the warmest and the coolest months. the highest temperatures occur in August; on any warm summer day the temperatures can reach as high as 35°C. The Bahama area is characterized by high relative humidity—the annual average is 76 percent. On a daily basis, the relative humidity in early morning hours is 85 or 90 percent and at the warmest time it is usually 60–70 percent. Rainfall is plentiful during May to October; the wettest month is September.

Observational Program

The field program included collection of surface and aircraft observations. In addition, we took time lapse as well as still cloud photographs. The Field Observing Facility (FOF) and Research Aviation Facility (RAF) of the National Center for Atmospheric Research (NCAR) at Boulder, Colo., provided data-gathering and logistic support for our program.

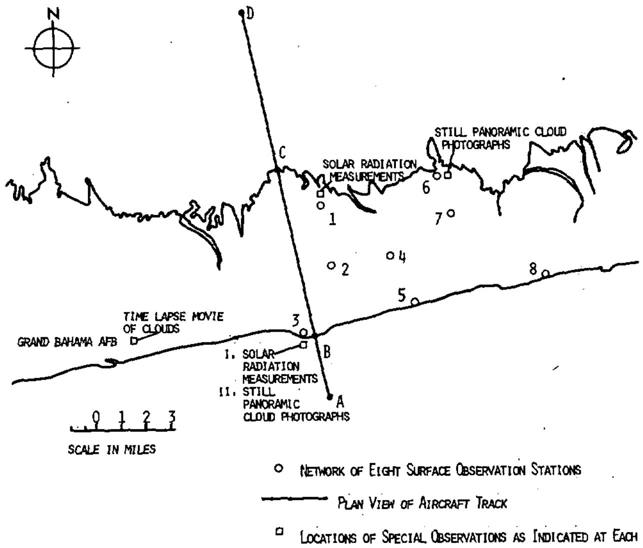

FIGURE 2.—Surface observational network and aircraft track.

TABLE 1.—Instrument locations by station number

	1	2	3	4	5	6	7	8
MRI mechanical weather station	X	X	X	X	X	X	X	X
FOF-540 (anemometer)	X	X	X	X	X	X	X	X
Thermograph	X	X	X	X	X	X	X	X
Hygrograph	X	X	X	X	X	X	X	X
Sol-a-meter	X		X					
Height of wind sensors	Tree top	Tree top	S*	Tree top	S*	S*	S*	S*

*Surface

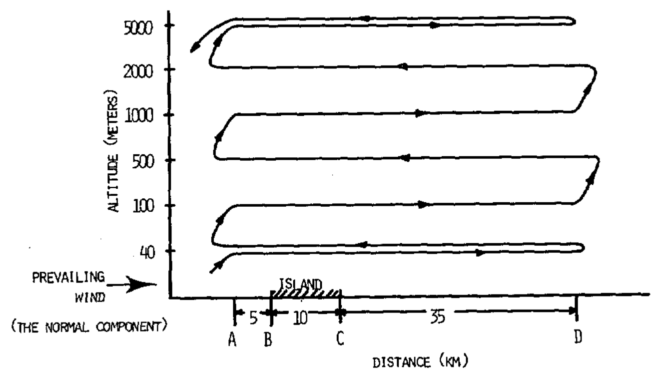

FIGURE 3.—Flight profile of the aircraft.

Figure 2 shows the network of eight stations that recorded conventional surface data such as temperature, relative humidity, and wind. Table 1 lists the instruments located at each station. In forested areas, the influence of trees on wind measurements was minimized by mounting the anemometers on 12-m towers—well clear of tree tops.

An instrumented aircraft—the NCAR Queen Air—measured temperature, humidity, and wind following a flight pattern shown in figure 3.[3] The flight profile consisted of straight and level traverses from point A (5 km upwind), across the island BC (10 km wide), to point D (35 km downwind). The location of the track ABCD relative to the island is shown in figure 2. The aircraft flew at altitudes of 40, 100, 500, 1000, 2000, and 5000 m, and the consistency of instruments was verified by repeating the traverses at 40 and 5000 m. We defined a "go" day as one which was not characterized by synoptic scale disturbances, and the Queen Air was programmed to make measurements only on go days. The takeoff times for three research flights, on any given go day, were 0700, 1130, and 1500 local daylight time (EDT) corresponding to 80°W longitude. The duration of each flight was approximately 2 hr.

In addition to the surface and aircraft data, the observational program also included the collection of the following two types of special observations:

1. Still, panoramic, black-and-white cloud photographs were taken from stations 3 and 6 (fig. 2). These pictures were taken through 360° moving clockwise from due north of the station. Such photographs are very useful in tracing the evolution and movement of clouds.
2. Time-lapse cloud movies were taken with a movie camera located at GBI, AFB (fig. 2) and pointing toward the general direction of the observing area. A new frame was exposed every 11 s. These movies can help us to delineate the clouds originating over the island.

While the surface observations were recorded around the clock, special observations such as cloud photographs (both still and time lapse) and aircraft observations were taken during daytime only.

[3] Mention of a commercial product does not constitute an endorsement.

3. OBSERVATIONAL RESULTS

Observations were made on site at Grand Bahama Island from Aug. 20–Aug. 29, 1970. In this section, we describe the observations of two selected days in relation to the heated island effect on the atmospheric circulations. These 2 days are Aug. 27 and 28, 1970. As shown by the satellite pictures, the study area on these 2 days was not affected by synoptic scale weather disturbances. This situation was also confirmed by the vertical time sections at Miami, Fla., Cape Kennedy, Fla., and GBI, which did not indicate any major synoptic scale perturbation in the wind pattern affecting the south Florida and the western Bahama region.

Figure 4 shows radiosonde and rawin soundings at GBI for August 27 and 28. Note that the temperature soundings are almost identical in the two cases; also, the winds for August 27 and 28 differ significantly in speed only.

On the basis of the features discussed, it appears that these 2 days are typically representative of the situation when the island could exert a significant influence on its atmospheric environment. We also have data that can perhaps enable us to examine the dependence of the perturbations (induced by the island) on the variations in wind, temperature, and moisture conditions of the prevailing large-scale flow.

Data Format

The recording thermograph, hygrograph, and anemometer at each of the eight surface stations provided a con-

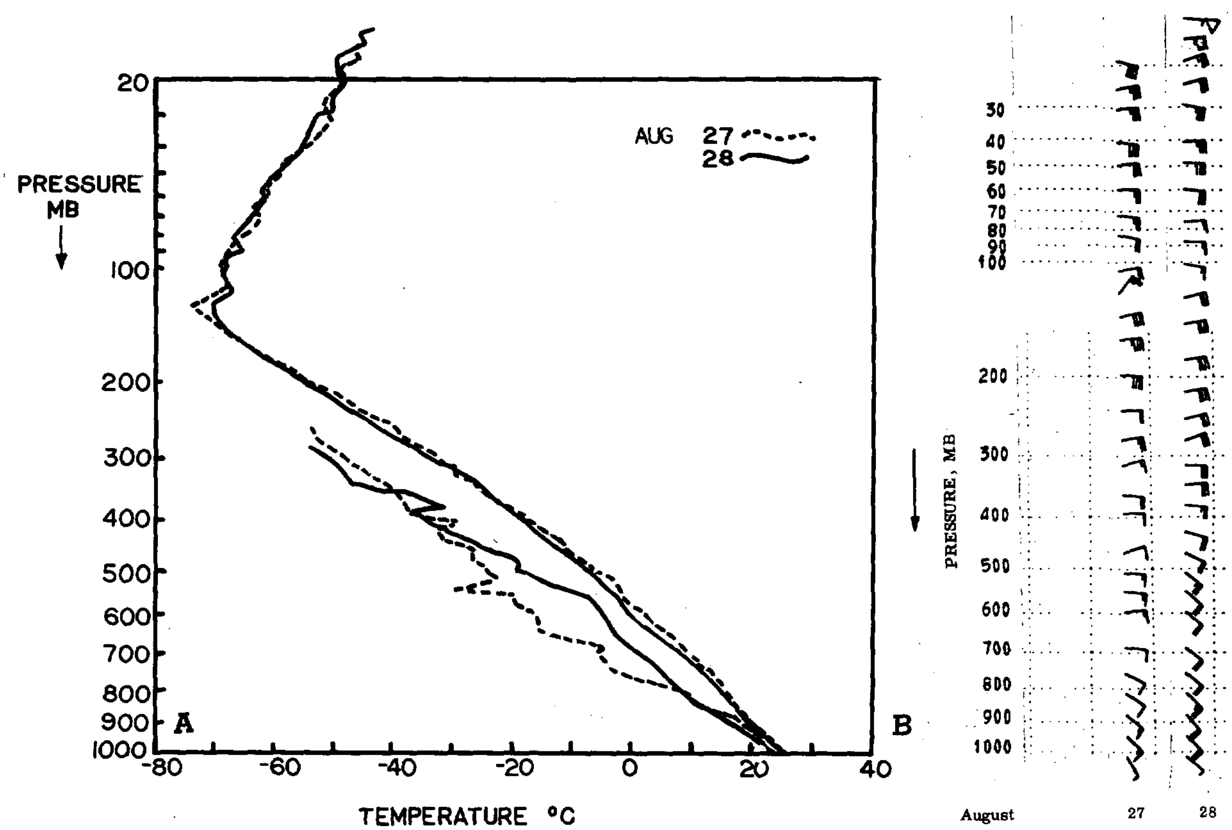

FIGURE 4.—Rawinsonde soundings [(A) temperature and humidity and (B) winds] at the Air Force Base, Grand Bahama Island, for 1200 GMT, Aug. 27 and 28, 1970.

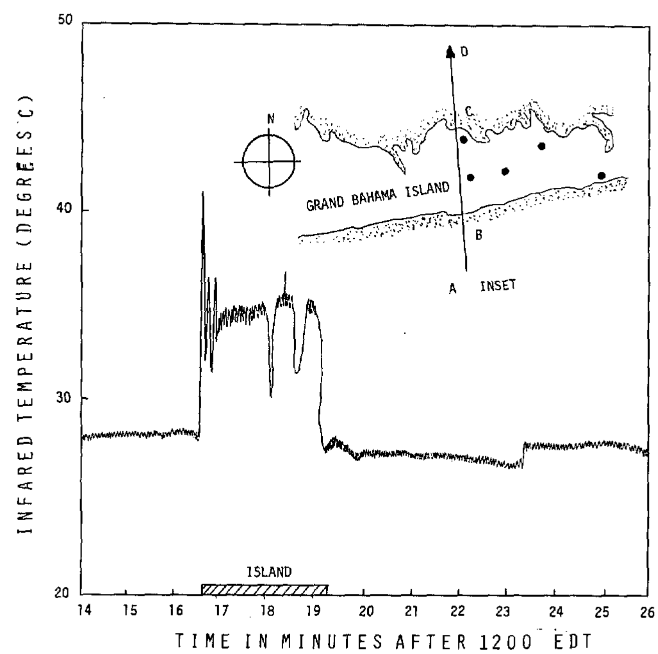

FIGURE 5.—Infrared surface temperature of the island measured by aircraft flying at a height of 40 m near noon on Aug. 28, 1970. Inset shows the flight track relative to the surface observational network.

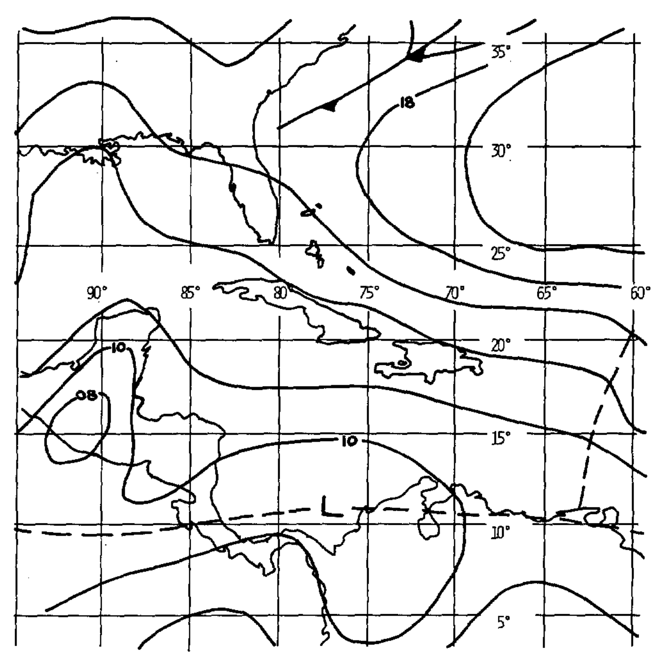

FIGURE 6.—Surface analysis for 1200 GMT, Aug. 27, 1970, in the vicinity of Grand Bahama Island.

tinuous record of temperature, humidity, and wind, respectively, on strip charts.

Composite mosaics have been constructed from still panoramic cloud photographs taken from station 3 during the daylight hours.

The instrumented Queen Air aircraft recorded surface infrared (IR) temperature, air temperature, humidity, and wind during its constant-level traverses at 40, 100, 500, 1000, 2000, and 5000 m along the track ABCD shown on the figure 5 inset. An example of a plot for the Barnes PRT-5 precision radiation thermometer-recorded tem-

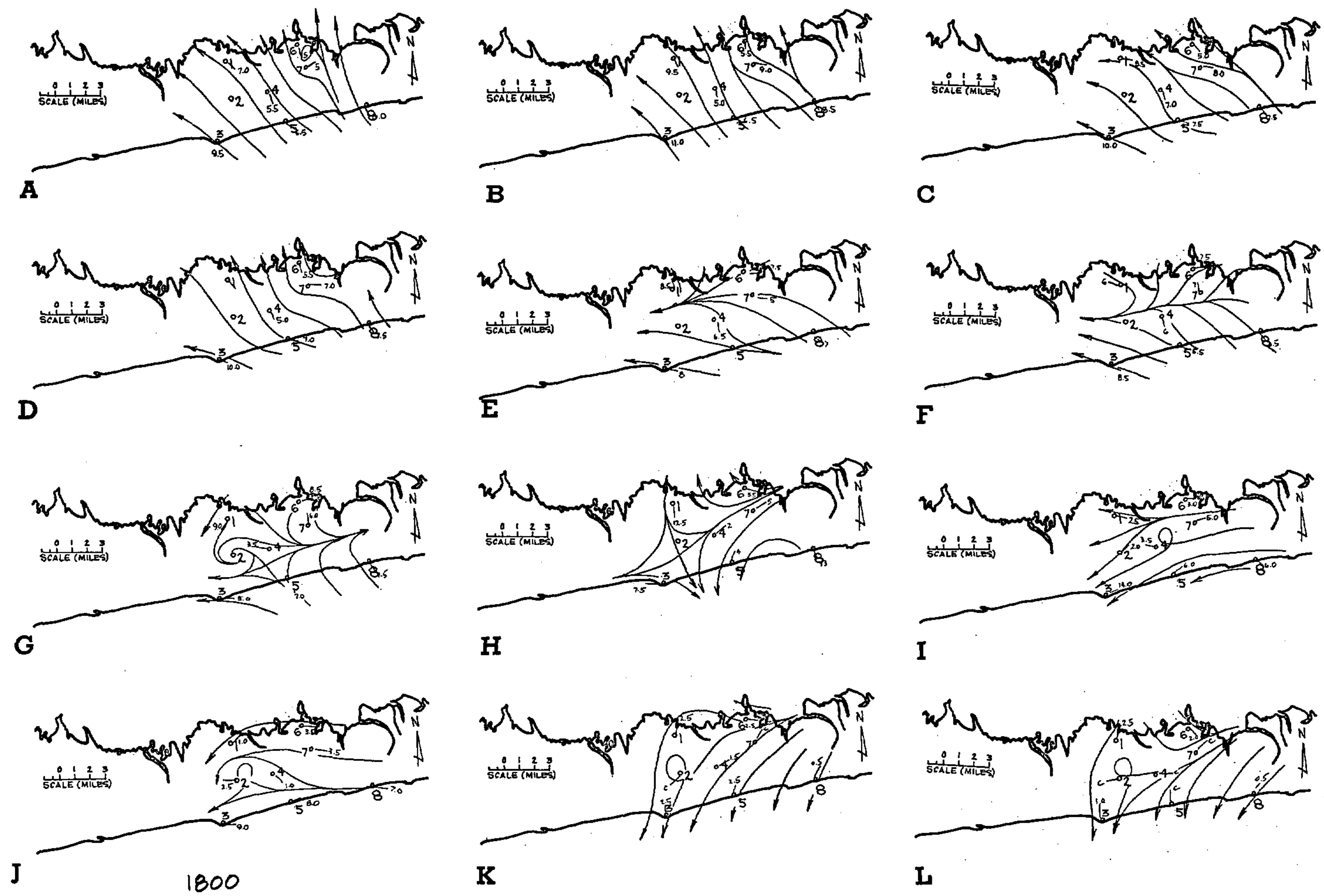

FIGURE 7.—Mesoscale analysis of hourly surface wind for (A) 0900, (B) 1000, (C) 1100, (D) 1200, (E) 1300, (F) 1400, (G) 1500, (H) 1600, (I) 1700, (J) 1800, (K) 1900, and (L) 2000 EDT, Aug. 27, 1970.

perature is shown in figure 5. This shows the surface temperature recorded during a noon-hour flight, on Aug. 28, 1970, when the island was about 6°C warmer than the surrounding sea surface.

We have also constructed vertical sections for air temperature from the data recorded by the Queen Air at six levels during morning, afternoon, and late afternoon flights. The sections also include the surface (IR) temperature recorded from 40 m. It may be noted that during any single flight, lasting approximately 2 hr, we had only one aircraft. Thus, in constructing these vertical sections it is assumed that the data at various levels were recorded simultaneously.

Accuracy of Instruments

The entire field program was supported and executed by the Field Observing and Research Aviation Facilities of NCAR. The instruments for surface observations as well as those aboard the aircraft were calibrated, installed, and maintained by NCAR personnel. The data were processed and made available to us in final format. We have used the data more or less in the form provided. After an inspection of the data—both surface and aircraft—we found that the surface data were generally good and consistent with the observed conditions. However, due to unfortunate malfunctions of recording systems, the aircraft data, with the exception of infrared temperature and some temperature traces at certain lower levels, were not recorded accurately. Consequently, the aircraft data have been used to the minimum extent possible; we believe that the basic results presented in this paper are not affected significantly by this.

Observations on August 27, 1970

Figure 6 shows the surface weather map analysis for Aug. 27, 1970. On this day, the western Bahamas and Florida regions were characterized by a weak ridge that extended through the entire troposphere. This resulted in a weak southeasterly/easterly flow from the surface to 200 mb. ATS 3 satellite cloud photographs showed very little cloudiness over GBI and vicinity. The absence of synoptic scale disturbances on Aug. 27, 1970, over GBI and the adjoining regions is clearly inferred on the basis of the prevailing meteorological conditions. Because of the absence of a synoptic scale disturbance, this day provides a good opportunity to study the influence of a heated island in producing intense perturbations in the prevailing flow.

The hourly evolution of the surface wind is shown in

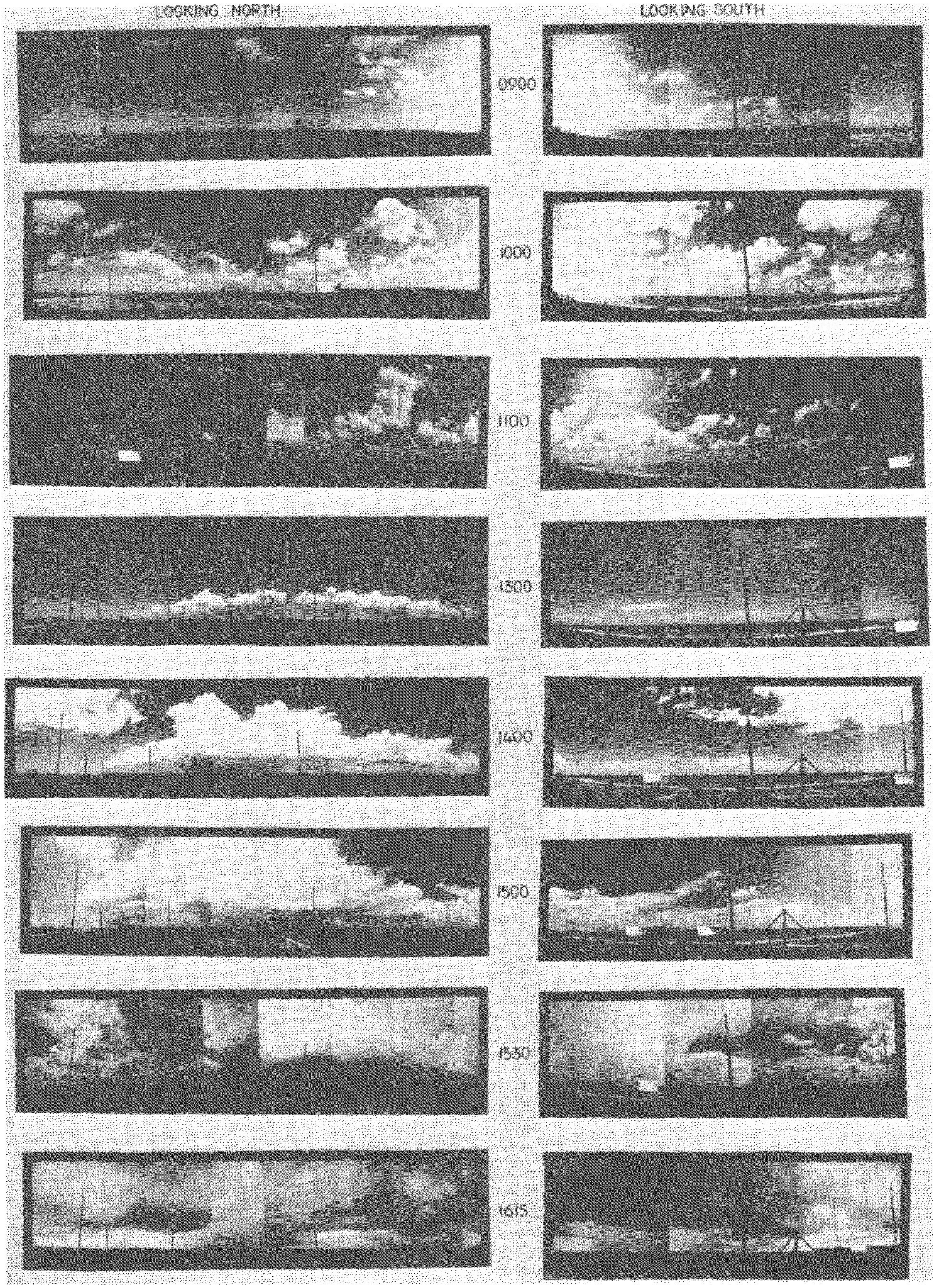

FIGURE 8.—Mosaic prepared from still panoramic cloud photographs taken from station 3 (on the south coast) on Aug. 27, 1970. Local standard times are given.

figure 7. During the morning hours, the wind (5 m/s, southeasterly) was almost normal to the island, and the streamlines did not show any significant patterns of confluence or diffluence. By 1300 EDT, an asymptote of confluence developed in the northern regions of the island. The confluence-convergence zone shifted south-

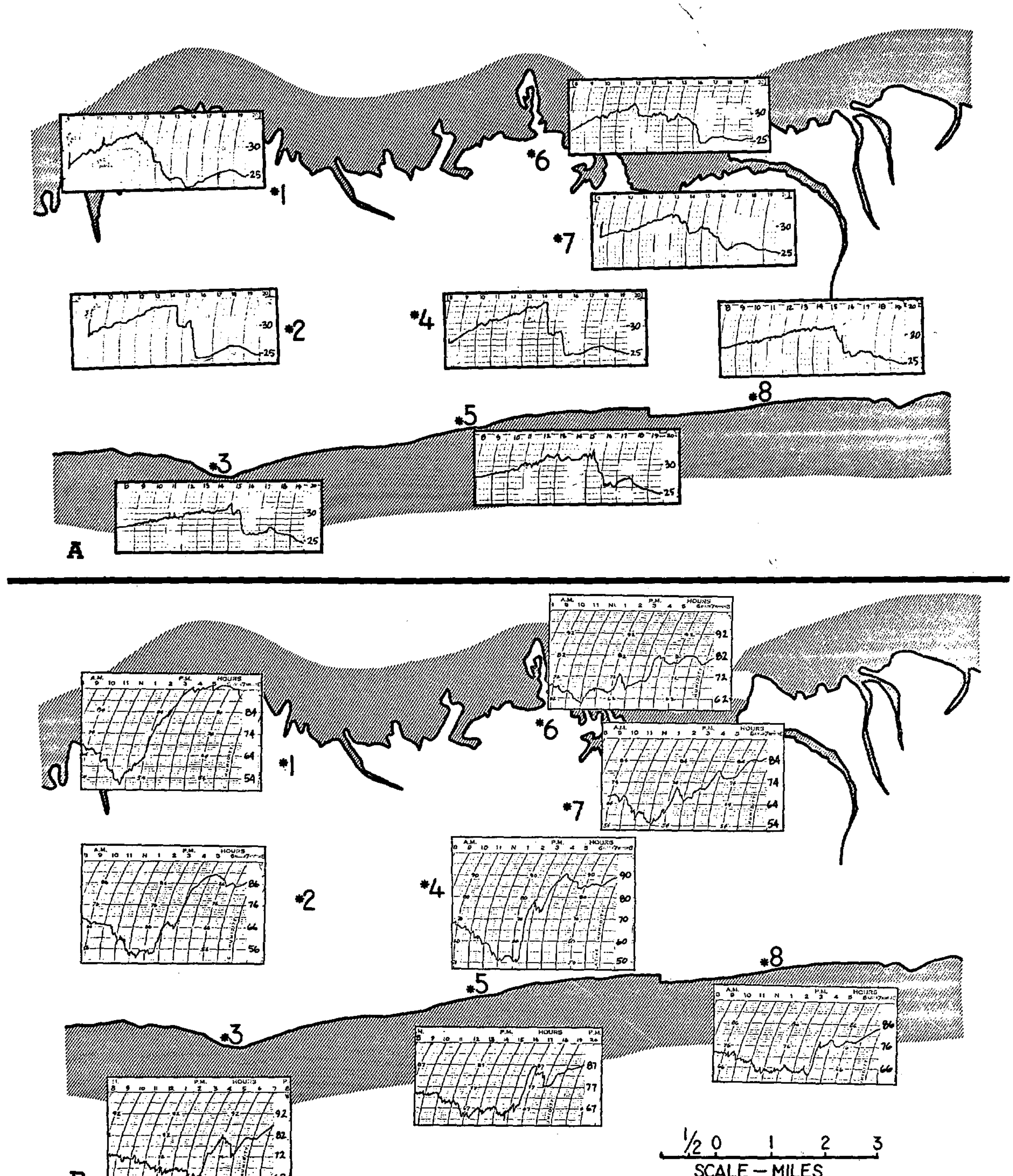

FIGURE 9.—(A) thermograph and (B) hygrograph traces for Aug. 27, 1970, at each of the eight stations of the surface network.

ward and became more pronounced between 1400 and 1500 EDT. The above feature in the wind field was very narrow ($\leq$ 2 km wide) and was found to coincide with the cloud line (fig. 8). This observed feature over Grand Bahama Island has remarkable similarity to the results published by Peace and Sykes (1966). They performed mesoscale analysis of a Lake Ontario storm characterized by a single, intense snow band and found that a pronounced narrow confluence line, about 2 km wide, in the low-level wind field coincided with the cloud band position. Figure 8 shows the panoramic cloud pictures taken from station 3 on the south coast. We note a shallow cumulus line to the north around 1300 EDT; the regions to the south, however, were almost cloudless at that time. This quiescent line of clouds moved southward and grew considerably during the next 3 hr as thundershower activity developed over the observing area of the island and in its vicinity. During this period, however, no significant changes occurred in the region of col over the open ocean. As shown by figure 12, the flow over the island returned to southeast direction on the next day.

The surface temperature and relative humidity for August 27 (fig. 9) followed normal diurnal variations at all eight stations of the network until 1200 EDT. At 1300 EDT, the temperature and relative humidity traces at

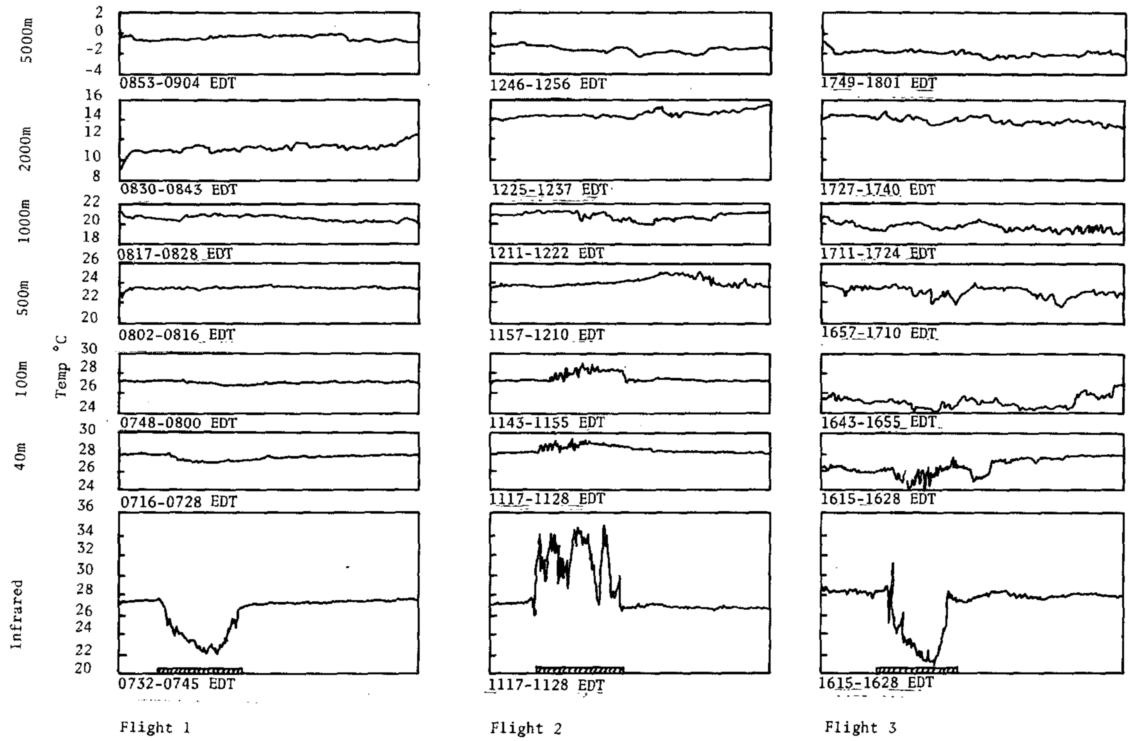

FIGURE 10.—Horizontal temperature profiles at different levels obtained by aircraft on Aug. 27, 1970.

northern stations 1 and 6 show perturbations in the diurnal trend. At this time, however, the temperature and humidity variations continued to follow the diurnal changes at the inland and southern stations. This points out that a disturbance (shown by wind field and also cloud pictures) formed to the north of the island at about 1300 EDT. Examination of temperature and humidity traces at 1400 EDT for stations 2, 4, and 7 shows that the disturbance propagated southward—the temperature fell and the relative humidity increased at these stations. Stations 3, 5, and 8 on the southern coast were still not affected by the disturbance. By 1500 EDT, the entire observing area was under the influence of the disturbance, which had by now grown in intensity. This is shown by the cooling of surface temperature and corresponding increase in relative humidity at all the stations of the network between 1500 and 1700 EDT. By about 1800 EDT, there was no disturbance over the island as shown by the slight increase in surface temperature after 1700 EDT. Since this occurred near sunset, the amplitude of the variations was small.

The aircraft observations of the surface and the air temperatures are depicted by means of a vertical cross section of the data recorded by the aircraft during morning, afternoon, and late afternoon flights on August 27. The most significant feature of this day is the similarity of the surface (IR) temperature trace for the morning and late afternoon flights (fig. 10). During late afternoon, disturbed conditions prevailed over the island and the rainfall had reached the island surface. Evaporation from this rain, as well as cutting off of incident solar radiation by clouds, made the island surface cooler than surroundings. The thermograph traces (fig. 9A) point out the cooling of the island surface and air over it. They also indicate that the temperature fell significantly only after the onset of rainfall, thereby suggesting that cloud shadow effect is considerably weaker than the evaporational cooling effect. The temperature profiles for flight 3 (fig. 10) show also that air over the island was cooler than the

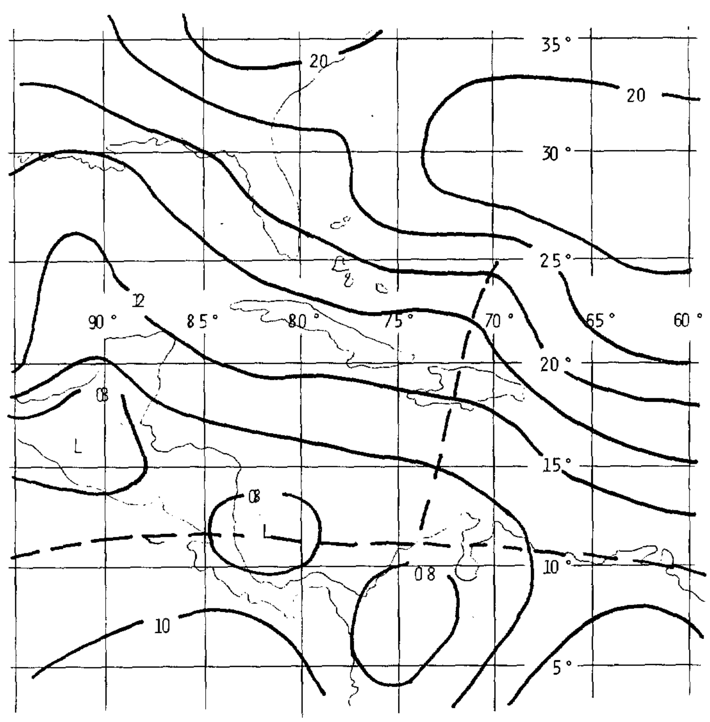

FIGURE 11.—Same as figure 6 for Aug. 28, 1970.

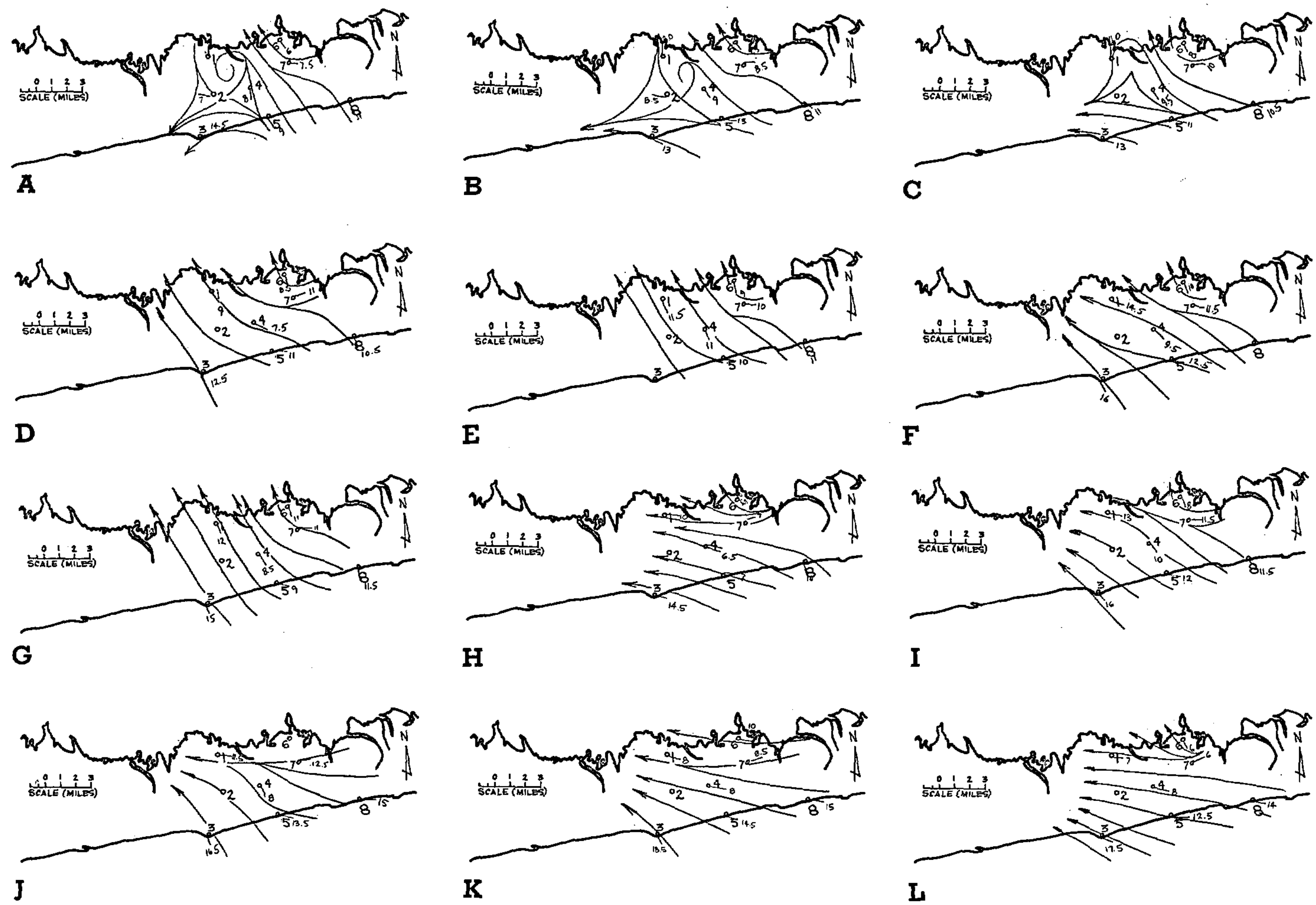

FIGURE 12.—Same as figure 7 for Aug. 28, 1970.

surroundings from the surface to 500 m. This cooling was probably due to evaporation from the rain.

The observed propagation of the disturbance in the upwind direction, with respect to the prevailing flow, can perhaps be attributed to the cooling of the atmosphere over the island. We suggest that evaporational cooling of air through a significant depth caused formation of a mesoscale high to the lee edge of the island, which accelerated the air in the upwind direction. The prevailing flow during this period continued to be as shown in figure 6—from the south-southeast. The time-lapse movies also confirm this picture.

In summary, on Aug. 27, 1970, a cloud line appeared to the north of the island in conjunction with the confluence in the wind field at 1300 EDT. The ensuing spread of cloudiness accompanied by intensification of rain had its effect on the diurnal cycle of temperature and humidity variations.

Observations on August 28, 1970

Figure 11 shows the surface weather map analysis for Aug. 28, 1970. The prevailing meteorological conditions over GBI and the vicinity on August 28 were similar to those on August 27; however, the anticyclonic conditions of the previous day had strengthened over the western Bahama region. In response to the development of an upper level Low over the central gulf coast, the ridge conditions over the Bahamas migrated northward and the southeasterly flow over GBI intensified. ATS 3 satellite pictures showed no significant cloud systems affecting the GBI area.

The hourly surface wind conditions for this day are shown in figure 12. The wind on August 28 is from the same direction but at twice the speed as that on the previous day. There was no tendency for any line of confluence in the wind field, and the corresponding cloud photographs (fig. 13) show generally suppressed conditions throughout the day except for some development to the north of GBI in late afternoon.

The surface temperature and humidity variations (fig. 14) did not depart significantly from the normal diurnal cycle. Small-amplitude perturbations in the temperature and humidity cycles at about 1600 EDT were confined to stations in the eastern part of the network.

The aircraft data (fig. 15) do not show any significant variations in the temperature traces.

In summary, on August 28, a relatively strong prevailing flow exerted a predominant advective influence and thereby prevented the development of any significant perturbations in the atmosphere due to the heated island effect.

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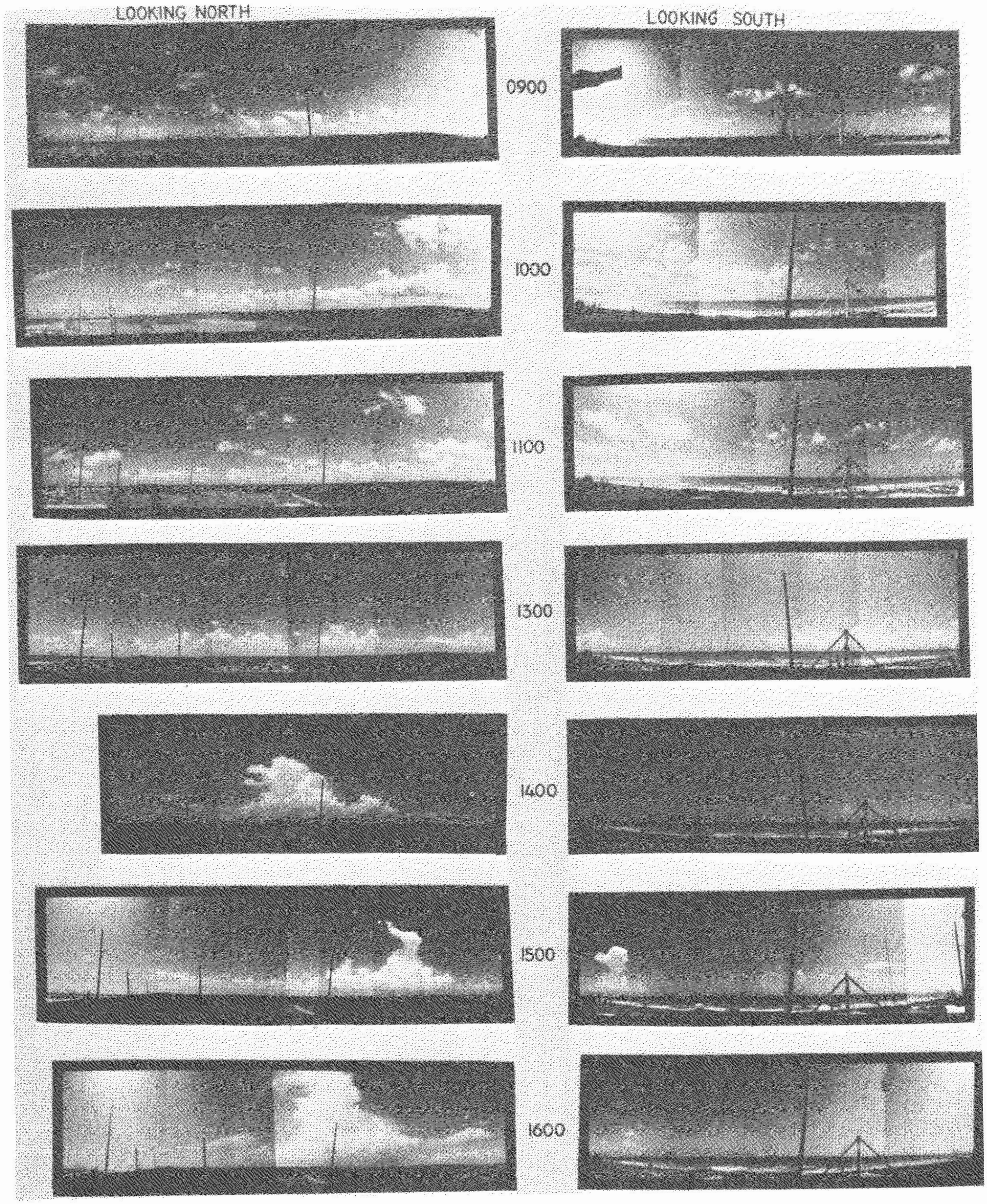

FIGURE 13.—Same as figure 8 for Aug. 28, 1970.

4. CONCLUDING REMARKS

The field program described in this paper was undertaken for a specific purpose; that is, to gather data that can be compared with the results of a two-dimensional theoretical model. We wish to emphasize that it is not our intention to use these observations to present a general

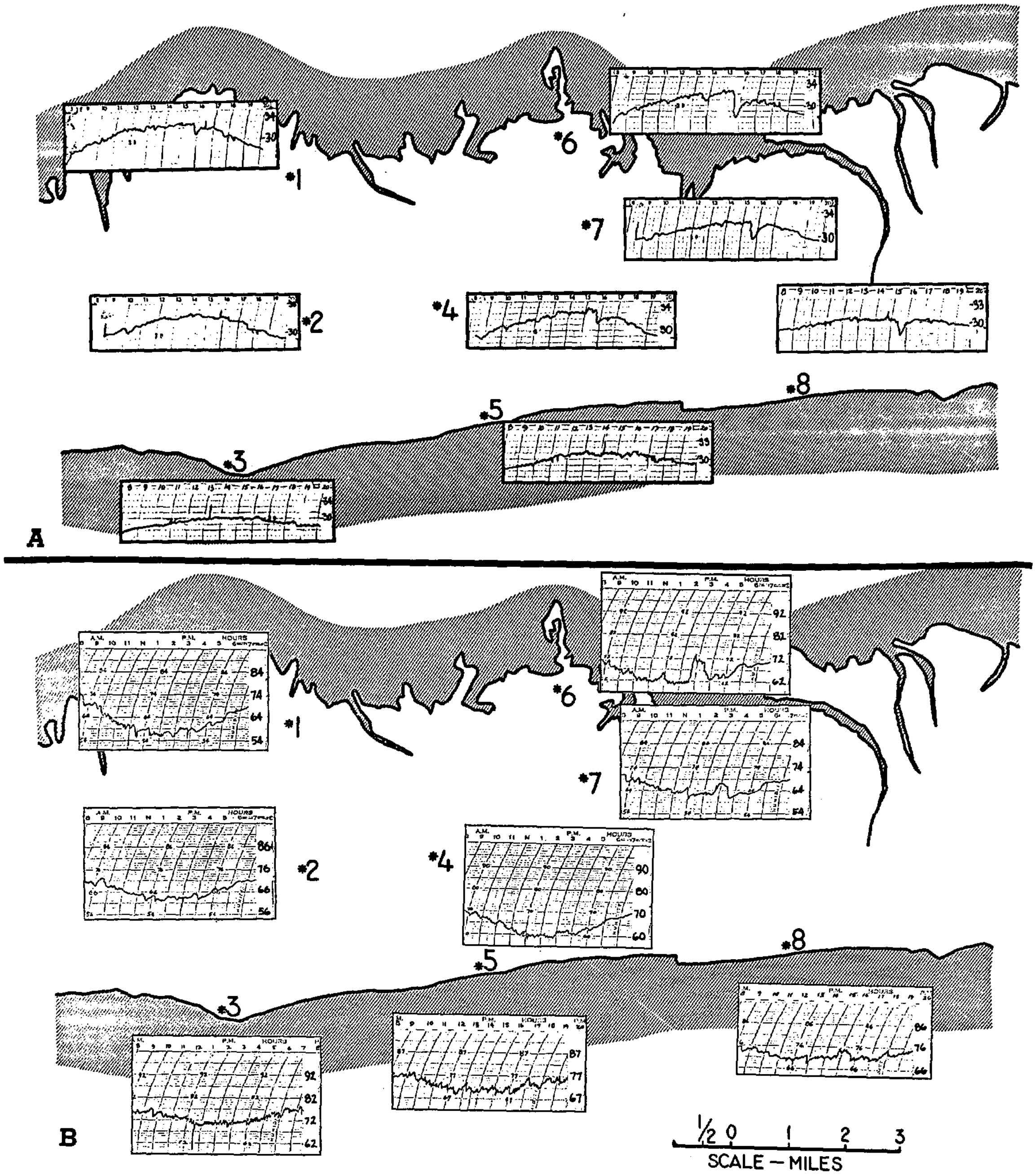

FIGURE 14.—Same as figure 9 for Aug. 28, 1970.

and universal picture of the heated island phenomenon. It will require a much bigger effort to demonstrate that the events described here occur systematically and repeatedly under similar conditions.

We believe, however, that within the limitations set by the objectives of the field program, finances, and other factors, we have collected observations that describe the influence of a heated island in a reasonably consistent manner. On the basis of the observations for the 2 days described and discussed in detail in earlier sections, the following points can be enumerated.

1. Even in the absence of large-scale (synoptic) disturbances (as on August 27), the heated island (GBI) can perturb the ambient atmosphere enough to cause disturbed weather conditions over and near the island. Under favorable atmospheric conditions of wind, moisture, and thermal stratification, rain can be induced by an island as small as GBI.

2. From the thermograph and hygrograph traces and the time-lapse cloud photographs for August 27, we can see that the leeward edge of the island is a preferred region for the formation of perturbations. This finding agrees with the observations of others, particularly Malkus (1963).

3. The observations indicate that the evaporational cooling of the ambient environment is an important factor in the behavior of induced circulations. We believe that this factor causes the propagation of the disturbance, formed initially on the leeward edge, in the upwind direction. Cooling of the earth's surface by the evaporation of rain also influences the induced convective disturbances. The influence of clouds on solar radiation reaching the

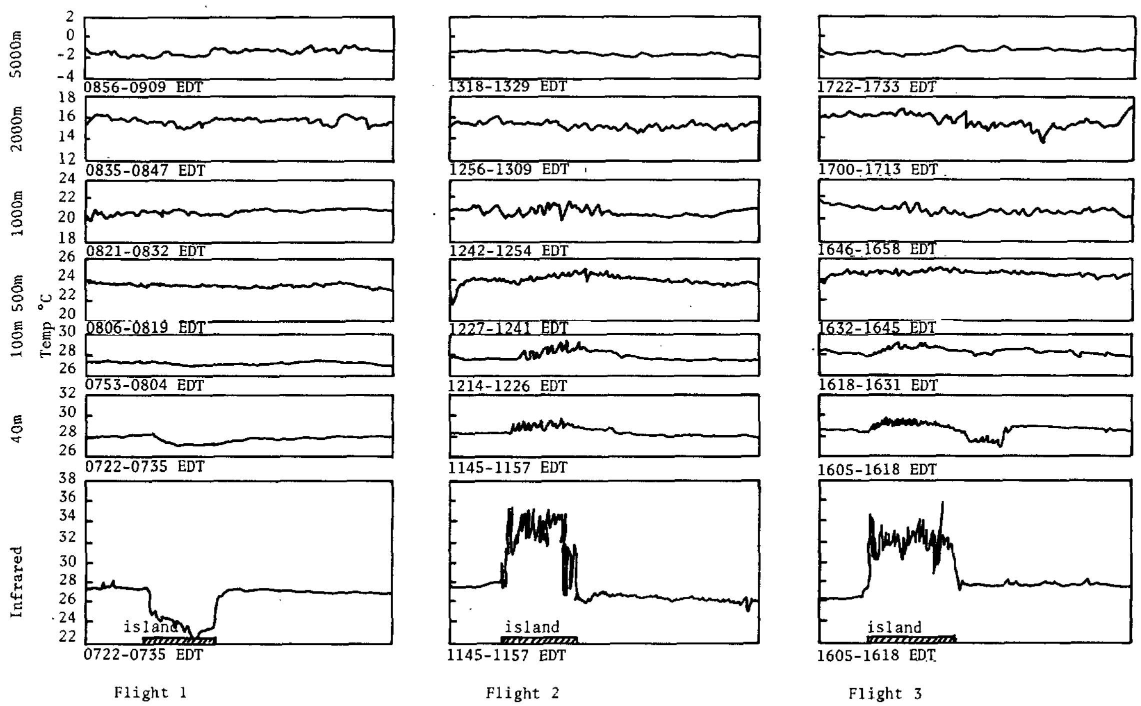

FIGURE 15.—Same as figure 10 for Aug. 28, 1970.

island surface is the least important.

4. In addition to the thermal and moisture structure of the prevailing flow, its direction and strength is an important consideration. The stronger prevailing flow (as on August 28) is not likely to perturb the atmosphere as much as the weaker flow from the same direction (as on August 27).

5. A disturbance induced by a heated island can perhaps be expected to last 3–3½ hr.

The above picture of the heated island effect is also supported by observations collected on other days during the 2-week period of the field program. These characteristics contrast sharply with those for days when no heated island effect could be observed because of the presence of synoptic scale disturbances.

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